

**AN ASSESSMENT OF TAILORING OF LIGHTNING PROTECTION
DESIGN REQUIREMENTS FOR A COMPOSITE WING STRUCTURE
ON A METALLIC AIRCRAFT**

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ABSTRACT

The Navy A-6E aircraft is presently being modified with a new wing which uses graphite/epoxy structures and substructures around a titanium load-bearing structure. The ability of the composites to conduct electricity is less than that of aluminum. This is cause for concern where the wing may be required to conduct large lightning currents. The manufacturer attempted to solve lightning protection issues by performing a risk assessment based on a statistical approach which allows relaxation of the wing lightning protection design levels over certain locations of the composite wing. This paper presents a sensitivity study designed to define the total risk of relaxation of the design levels.

INTRODUCTION

The new A-6 wing design uses graphite/epoxy structures in an effort to minimize weight while maximizing the strength and life of the wing (design life of 4400 hours). The flight control surfaces (i.e., slats and flaps) and aircraft fuselage are of metallic construction. The graphite/epoxy structures are connected to the inner wing by metal rivets. They are present in the wet wing area (fuel is contained behind these panels) as well as other areas which do not contain fuel. The composite panels do not conduct electricity as well as the aluminum they replace. This is cause for concern where the wing is required to conduct large lightning currents as a result of direct stroke attachment. Lightning channel attachment to the aircraft structure and/or wiring can result in damage to the aircraft surface and wiring. Traditional protection from direct attachment lightning effects consists of establishing a low impedance path between any two points where the lightning induced currents will flow. The Navy normally requires that aircraft meet the requirements of MIL-E-6051D and MIL-B-5087B when tested to the waveforms and specifications of MIL-STD-1757A. MIL-E-6051D outlines the overall requirements for systems electromagnetic compatibility (EMC). MIL-E-6051D stipulates that lightning protection be guided in accordance with direction given in MIL-B-5087B. MIL-B-5087B specifies that protection for lightning requires that bonding allow discharge current to be carried between the extremities of an aircraft without risk of damage to flight controls or producing sparking or voltages within the vehicle in excess of 500 volts. These requirements are based on a lightning current waveform of 200 kA peak, a pulse width of 5 to 10 microseconds and a rate of rise of 100 kA per microsecond. MIL-B-5087 also gives the following guidance for aircraft vehicle skin: "Vehicle skin shall be so designed that a uniform low-impedance skin is produced through inherent RF bonding during construction. RF bonding

must be accomplished between all structural components comprising the vehicle". MIL-STD-1757A presents the standardized set of test waveforms and techniques to be used to qualify aerospace vehicles and hardware for lightning. The tests are designed to define the physical effects of lightning induced current and its interaction with fuel, structural and electrical hardware as well as indirect effects associated with strikes coupling to internal wiring and electronics. Lightning strike zones are defined dependent on attachment or transfer characteristics. Three major surface zones are identified. Zone 1 defines surfaces where there is a high probability of initial attachment. It is further broken down to Zone 1A and Zone 1B. Zone 1A is an initial attachment point with a low probability of flash hang-on (such as a leading edge). Zone 1B is an initial attachment point with a high probability of flash hang-on (such as a trailing edge). This zone should be designed to withstand direct strike lightning components up to 200 kA. Zone 2 defines surfaces for which there is a high probability of a lightning flash being swept by the airflow from a Zone 1 point of initial attachment. Zone 2 regions also subdivide into 2A and 2B, dependent on the probability of flash hang-on. Zone 3 surfaces are required to conduct the induced current between any two Zone 1 regions but are not subject to direct attachment effects. Figure 1 depicts the MIL-STD-1757A direct strike waveform components A, B, C, and D for required levels of protection, dependent on zoning. Another military standard (MIL-STD-1795A) also gives lightning design guidance for aerospace vehicles. It more clearly defines the concept of tailoring the lightning protection design requirements. It states that identification of zoning can be accomplished by use of analysis, attachment tests, similarity or any combination of these methods. It states that the direct effects waveform components A, B, C and D of MIL-STD-1757A should be used for design and verification purposes.

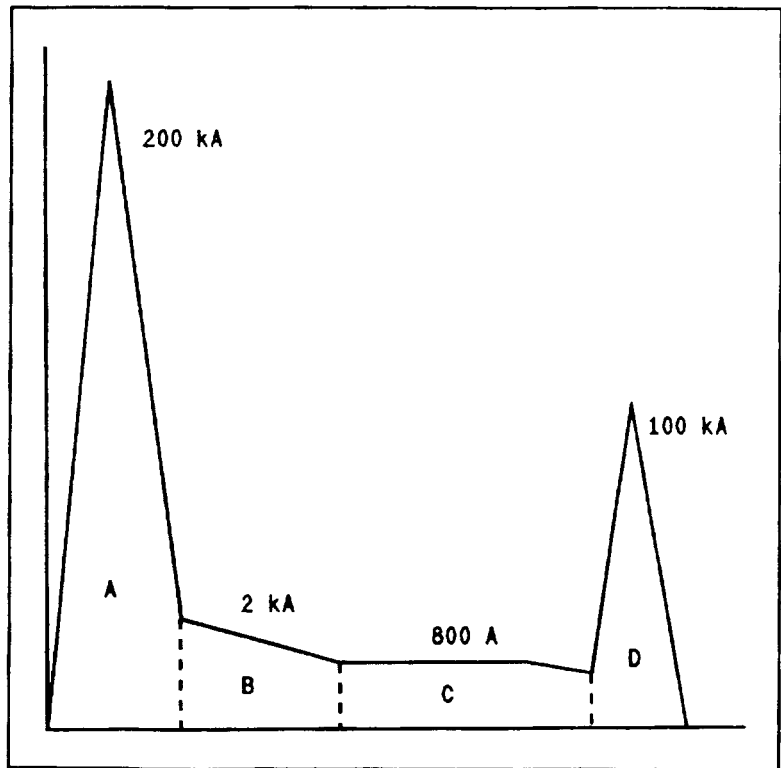


Figure 1. MIL-STD-1757A Current Components.

The uniform low-impedance requirement stated in MIL-B-5087B can normally be met by an all aluminum aircraft, but is much more difficult for one which is constructed with multiple materials which consist of many different electrical properties. The direct attachment requirements levied by MIL-STD-1757A and MIL-STD-1795A can normally be met by an all aluminum aircraft. Lightning testing has shown that composite structures and substructures behave differently than aluminum and indeed can be damaged by the large induced lightning currents specified in MIL-STD-1757A and MIL-STD-1795A. Herein lies the dichotomy of terms: The A-6 composite wings

consist of high-impedance composite panels attached to a medium-impedance titanium spar with low-impedance metallic fasteners and in electrical contact with low-impedance aluminum flight control surfaces. A uniform low-impedance skin is not possible in this configuration. The manufacturer of the A-6 composite wing attempted to solve this dichotomy by applying a MIL-STD-1795A approach by performing a risk assessment based on analytical and statistical data. The methodology entailed definition of a probabilistic approach towards lightning design criteria as related to maximum lightning current amplitude and expected location of strike on the aircraft. The analysis considered wing surface zoning, scale model lightning strike lab studies, a computer simulation of lightning strike locations, lightning strike rates on tactical aircraft and lightning threat statistics.

THE ANALYSIS

The analysis was based on definition of risk measure factors to establish the lightning protection design requirements. The risk measure factors included the number of wings, the flight hours guaranteed for each wing, the number of lightning strikes expected per flight hour, the lightning threat statistics based on Cianos and Pierce [1] and the percentage of lightning strikes predicted to specific wing areas. The Cianos and Pierce lightning charts define two threats (severe and moderate) as shown in Figure 2. The severe threat (upper curve) was equated to a MIL-STD-1757A component A for definition of the Zone 1 threat. The moderate threat (lower curve) was equated to MIL-STD-1757A component D for definition of the Zone 2 threat. The number of wings times twice the total guaranteed flight hours per wing defines the total flight exposure (taking into account a safety factor of two). The total flight exposure times the lightning strikes per hour (the manufacturer used 1 in 64,000 flight hours as defined by Corbin [2]) defines the total strikes expected during the life of the wing. If the probability of the lightning strike distribution on the aircraft is known then the strike probability to individual aircraft areas can be defined. The lightning zone definition was accomplished by test of a 1/25 copper coated scale model at LTRI, Miami, Florida. The wing area definition is shown in Table I.

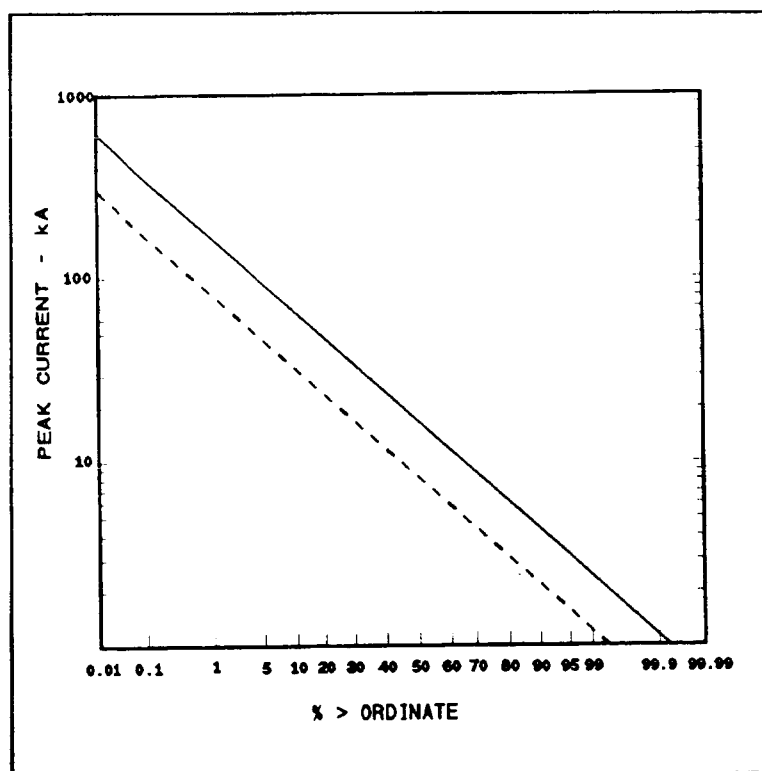


Figure 2. Cianos and Pierce Lightning Probabilities.

Table I. A-6E Wing Lightning Strike Category Definition.

WING AREA	CONFIGURATION	DESCRIPTION	ZONE
1	SLATS EXTENDED (10% of Flt)	OUTBOARD SLAT TIP	ZONE 1
		WING AREA AFT OF SLAT TIP	ZONE 2A
2	OUTBOARD FENCE UPPER WING	OUTBOARD FENCE	ZONE 1
		18" EITHER SIDE	ZONE 2A
3	LARGEST STORES STATIONS L, 1, 2, 4, 5, R	FRONT TIPS STRUCK FROM SLIGHTLY ABOVE HORIZON	ZONE 3 (STORE/WING INTERFACE)
		18" EITHER SIDE ON UPPER SURFACE	ZONE 2A
4	LARGEST STORES STATIONS L, 1, 2, 4, 5, R	ALL POINTS ON WING STORES INCLUDING TIPS, EXCLUDING FROM SLIGHTLY ABOVE HORIZON	ZONE 3 (STORE/WING INTERFACE)
5	ALL CONFIGURATIONS	WING TIPS	ZONE 1

The probability model then used this test data in the following lightning strike probability model:

$$C(t, a) = L_o t \sum_{i=1}^k P_i Q(a_i) \quad (1)$$

Where:

- C = Risk Measure (the expected number of lightning strikes with amplitudes greater than the design value)
- L_o = Lightning strikes per fleet flight hour
- t = Hours exposed to lightning (number of A-6 wings times twice the guaranteed flight hours)
- k = Number of wing areas (5)
- P_i = Probability of strike to critical wing area
- Q(a_i) = Probability that strike exceeds design.

A risk factor was assigned to each wing area (1 - 5) such that the total number of strikes which would be allowed to the total wing in excess of the design level over twice the wing lifetime was 0.5. This risk factor was distributed evenly over the five wing areas. This allowed calculation of q(a_i) at each of the wing areas. Using this value as the known variable one could then enter the Cianos and Pierce chart to identify the respective unknown design value for the lightning current. Table II presents the calculated lightning attachment design levels identified as a function of wing areas. The lightning design requirement included the protection for Zone 1 and Zone 3 regions to the full 200 kA requirement. Wing area 3 (Zone 2A) was specified at 40 kA, well in excess of the identified design level of 15 kA.

Table II. A-6 Calculated Wing Strike Probabilities and Threat Levels.

WING AREA	P_i (LAB DATA)	$q(a_i)$ X 100%	a_i		RISK FACTOR
			ZONE	CURRENT	
1	$0.1 \times 6/132 = 0.00455$	4.0%	1	25 kA	0.1
			2A	13 kA	
2	$2/330 = 0.00606$	38%	1	34 kA	0.1
			2A	17 kA	
3	$1/195 = 0.00510$	36%	3	30 kA	0.1
			2A	15 kA	
4	$9/198 = 0.0455$	4.0%	3	110 kA	0.1
5	$106/330 = 0.321$	0.57%	1	220 kA	0.1

TOTAL RISK FACTOR 0.5

This approach was accepted by the Navy. The strike rate was modified, however, to a rate of 1 in 3362. The strike rate chosen by the manufacturer was one of the least stressing strike rates reported by Corbin. The strike rates discussed in the Corbin data ranged from 1 in 2,000,000 to 1 in 2,500. All of these values were related to peace time civilian flight and were not considered as adequate for an all weather attack aircraft.

One concern associated with this statistical tailoring approach was the use of total exposure time as a variable. (i.e., if the number of wings procured decreased then this decreases the total exposure of the wing in the lightning environment which in turn can decrease the specification level). In an attempt to minimize the impact of number of wing sets on the statistical analyses the strike data was normalized to include only single wing events. This allowed calculation of a risk factor for each wing area using the 200 kA and 40 kA levels identified by analysis and the 200 kA and 100 kA levels specified by MIL-STD-1757A. These comparisons took into account restrikes as a result of swept strokes. Information presented by Fisher, et al. [3] indicates a restrike rate which can vary between 20 msec and 200 msec. The incorporation of restrikes in swept stroke regions (Zone 2) alters the P_i value in the wing areas 1 and 3. A comparison of the increased of strikes expected above the design criteria as a function of design level is shown in Figure 3.

Several mitigating factors were taken into account during the specification tailoring effort. These factors included: (1) The use of only cloud-to-ground lightning and peace time strike data for definition of the lightning threat variable; (2) The Navy's use of JP-5 fuel; (3) The data from previous composite direct attachment testing which indicated that lightning induced currents on composites usually resulted in low energy arcing from the composite material [4-7]; and, (4) The A-6 automatic Halon fire extinguisher. The mitigation factors are

discussed in more detail below:

Cloud-To-Ground Lightning

Definition. A tactical aircraft will experience an airborne lightning environment which includes both cloud-to-ground and cloud-to-cloud lightning events. The Atmospheric Electricity Hazards Protection Program (AEHP) discussed by Beavin [9] was an attempt to measure the lightning threat to tactical aircraft. In the early stages of the program there were few lightning strikes for each thunderstorm penetration.

The majority of penetrations were attempted at or below the freezing level (levels < 16,000 feet) as a result of previous observed lightning interactions with aircraft as reported by Corbin [2]. The rate of strikes at this altitude resulted in few direct lightning strikes. Using new procedures the NASA test aircraft encountered frequent strikes on penetrations in the vicinity of 20,000 feet. This would lead the reader to conclude that the cloud-to-cloud aircraft/lightning interaction is more probable. There are other factors, however, which reduce these cloud-to-cloud aircraft/lightning interaction probabilities. Aircraft flying above 20,000 feet have more latitude in their flight path and can more easily "see and avoid" the thunderstorm cells. Aircraft in a take-off, departure, penetration, approach or landing pattern (< 15,000 feet) are more confined in their flight path due to flight path restrictions imposed by FAA for aircraft separation and obstacle clearance requirements. As a result the "see and avoid" capability is often not possible, therefore exposing the aircraft to increased cloud-to-ground aircraft/lightning interactions. Additionally, most tactical aircraft have established procedures for thunderstorm penetration as directed in the aircraft type Naval Air Training and Operating Procedures Standardization (NATOPS) manuals. The direction given in these manuals is: "Unless the urgency of the mission precludes a deviation from course, intentional flight through thunderstorms should be avoided to preclude the high probability of damage to the airframe and components by impact of ice, hail and lightning ... If circumnavigation of the storm is impossible, penetrate the thunderstorm in the lower third of the storm cell..." The possibility of physical damage to the aircraft at the higher altitudes due to hail and ice result in procedures which enhance the cloud-to-ground aircraft/lightning interaction probabilities. The amount of mitigating effect to the actual aircraft by definition of threat using cloud-to-ground interactions is therefore reduced.

JP-5 Flammability. Flammable vapors can be ignited if the correct concentration of fuel-to-air mixture and temperature are present when introduced to a sufficient ignition source. A

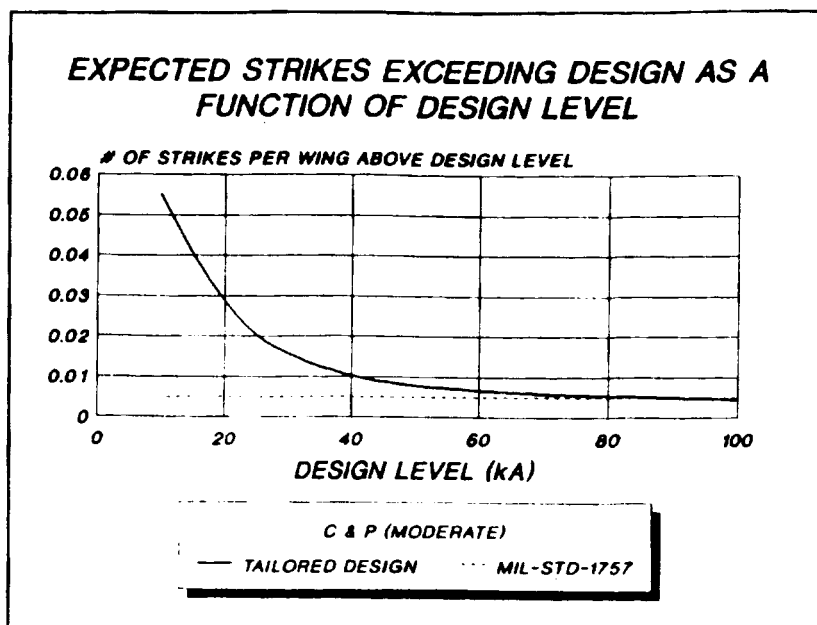


Figure 3. Tailored Design Levels VS MIL-STD-1757A.

vapor/air mixture is too rich to burn if there is insufficient vapor space in the fuel tank, as is the case in a fully fueled wing. A vapor/air mixture is too lean to burn if the vapor space is too large. Ignition of JP-5 requires that very high temperatures (> 104 degrees Fahrenheit) be associated with altitudes below 10,000 feet. Any mixture of JP-5 and JP-4 significantly reduces this level of protection. The case of a fuel mixture occurs for Navy aircraft if joint Navy/Air Force operations are conducted and Navy aircraft are refueled in-flight by Air Force tankers (the Air Force uses JP-4 fuel). This mitigation effect is therefore reduced during joint operations.

Composite Material Low Energy Arcing. The source of ignition must be present at the same time the vapor/air mixture can sustain combustion. This source must produce sufficient energy to produce a minimum combustion flame to sustain ignition. Ignition can occur as a result of sparking or hot spot interaction with the fuel/vapor mixture. Numerous laboratory tests and analyses have been conducted to ascertain effects of lightning currents to composite material which enclose fuel tanks [4-7 and 16-19]. Tests comparing the hot spot time/temperature characteristics of carbon epoxy (C/E) and aluminum panels indicate that for swept stroke lightning the aluminum panels get hotter, but their peak temperatures and thermal dissipation occur two orders of magnitude faster than the C/E panels. The conclusions were that there is a considerable margin precluding hot spot ignition of fuel behind composite materials.

Fay Sealant At Wing Joints And Fasteners. The most significant lightning fuel ignition hazard was found to be interior sparking at the interface of adjacent materials or at fasteners. This can occur for both aluminum and composite materials. It is normally caused by poor conductivity between the interface materials as a result of gaps or voids between the main conduction channel (the fastener) and the adjacent material (the aluminum or composite panel). The spark shower which can occur for untreated adjacent materials or fasteners can be of sufficient magnitude to cause fuel ignition given the correct vapor/air mixture. The probability of arcing is higher for composite panels because of the poor conductivity as a result of interface surface irregularities. Additionally, in composite panels with fasteners, swept stroke testing has indicated that lightning has a tendency to attach to the fasteners regardless of panel material. [7] The composite wing incorporates a fay sealant internal to the fuel tank at these interface joints in order to mitigate these effects. This sealant provides the primary protection for high energy spark mitigation as a result of direct effects lightning induced currents in wing Zone 2 regions. The sealant is designed to prevent arcing by suppressing the heated matter away from the fuel.

Halon Fire Extinguishing System. The A-6E composite wing has an additional survivability feature designed into the aircraft to preclude fuel fed fire. The wing incorporates a Halon fire extinguisher system which may be activated in the anticipation of combat operations. When activated the vapor/fuel void is monitored for sufficient energy which would ignite the vapor/fuel mixture. Upon sensing auto-ignition of the fuel the system will discharge the halon into the void to extinguish the fire. This system can only be activated once in-flight and requires reset/recharge upon landing in the event it is activated but not used.

RESULTS

In order to more completely evaluate the effect of the multiple variables which were

utilized for the statistical analysis a sensitivity study was accomplished where each variable utilized in the analysis was given an upper and lower bound. The lightning amplitude threat definition was varied, the restrike rate was varied and the strike rate was varied. The change to the design level as a result of altering each of these variables is addressed below.

The Threat Variable. Numerous studies have been accomplished to date regarding the lightning threat [8-14]. Melander and Axup reported [10 and 13] that measurements of lightning currents on towers could be suspect data. Berger and Garbagnati measurements were taken on towers in mountains of Switzerland and Italy. Uncertainties can arise with data due to the presence of tower on rocky mountain. Larger amplitude strokes are thought to strike tall towers. Also it is thought that positive strikes are more prevalent at higher altitudes where the towers were located. Recently Podgorski [15] completed a study of lightning strikes on a tall tower and reported that the peak current distributions of lightning in cloud-to-ground strikes indicate that the lightning measurements of Berger were accurate. These and the tall tower measurements were compared to the Lightning Positioning and Tracking System (LPATS) network measured data from Atmospheric Research System Inc. to define the low probability occurrence distribution of data. The probability distribution of peak lightning currents was also evaluated for the data from the Lightning Direction Finders (LDFs). A unified lightning threat was derived for aircraft near/on ground (within 1000 meters) and in-flight. The results of variation of the lightning threat show that slight divergences (an increase from 0.008 to 0.015 strikes per wing above design level) exist at the higher design levels (> 70 kA) to major divergences (an increase from 0.008 to 0.05 strikes per wing above design level) exist below design levels of 20 kA.

The Restrike (Swept Stroke) Variable. The aircraft speed and physical wing dimensions were driving factors. Three values (0, 4, and 10 restrikes) were chosen based on the calculated boundaries using information on restrike rates identified by Fisher [7]. The impact of variation of restrikes while holding all other variables constant is shown in Figure 4.

The Strike Rate. The strike rate data (1 in 3362) was Navy aircraft historical lightning strike rate data and considered only peacetime operations. A number of Navy pilots interviewed stated that it was their opinion that a number closer to 1 in 500 would be a more realistic strike rate. Although the historical Navy tactical aircraft strike data indicated a rate closer to 1 in 3362 the number of events may be understated. This seems to be borne out by the interviews. Since the strike rate was tied to more of "see and avoid" peace time operations the 1 in 500 number was established as the upper bound (i.e., wartime operations), the 1 in 3362 as the median (i.e., normal ship based operations), and 1 in 10,000 as the lower bound (i.e., shore based operations). Figure 5 shows the result of variation of the strike rate. The rate of 1 in 500 shows a significant deviation in the vicinity of 60 kA and diverges exponentially below the 40 kA design level.

The consequence of exceeding the lightning design protection can range from minor upset or damage of aircraft systems and subsystems to complete loss of aircraft due to fuel tank explosion. The worst case over-design strike could occur because the Zone 2 restrike region (wing area 3) can become Zone 1 due to migration of the Zone 1 initial attachment point onto the wing. The distance as related to the migration of the initial attachment position on the wing

along the flight path are shown in Table III.

The dotted line in Table III indicates where the wing area 3, Zone 2 transition occurs. The region to the left of the line indicates the migration does not impact the composite panels on the top of the wing. The region to the right of the line indicates the initial attachment migration results in a Zone 1 threat of 200 kA can occur on the composite panels. The case of fuel ignition as a result of puncture or burn-through and direct interaction of the lightning current with the fuel is a possibility. Aluminum will exhibit burn-through in relation to the lightning dwell time. If the channel of 100 kA were to maintain the same relative position on the aircraft for a period of over 50 msec then burn-through is possible. The equivalent sized composite panel without fasteners does not exhibit burn-through. The composite panel with fasteners, however, exhibited burn-through at dwell times below 1 msec. The lightning threat dwell time for Zone 1A and 2A in accordance with MIL-STD-1757A is approximately 500 microseconds. This could be cause for concern.

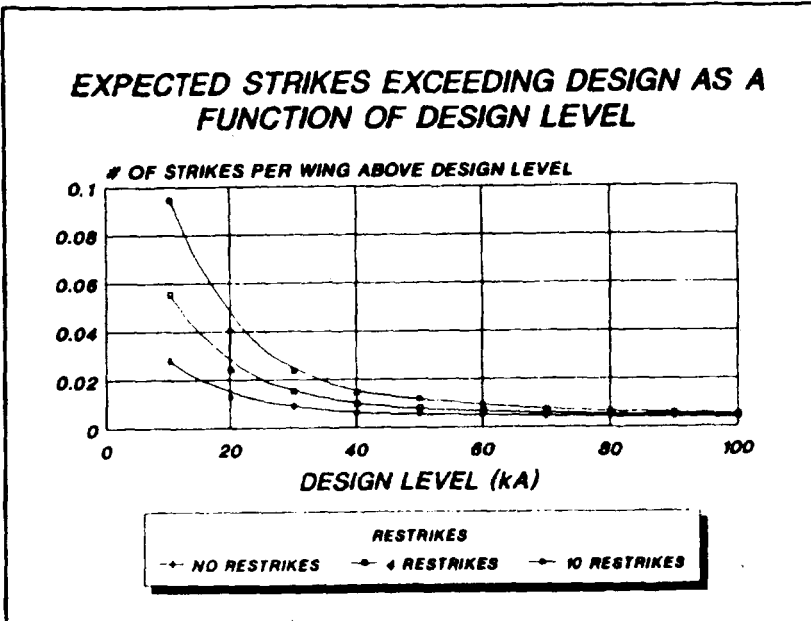


Figure 4. Impact of Changing Restrike Rate.

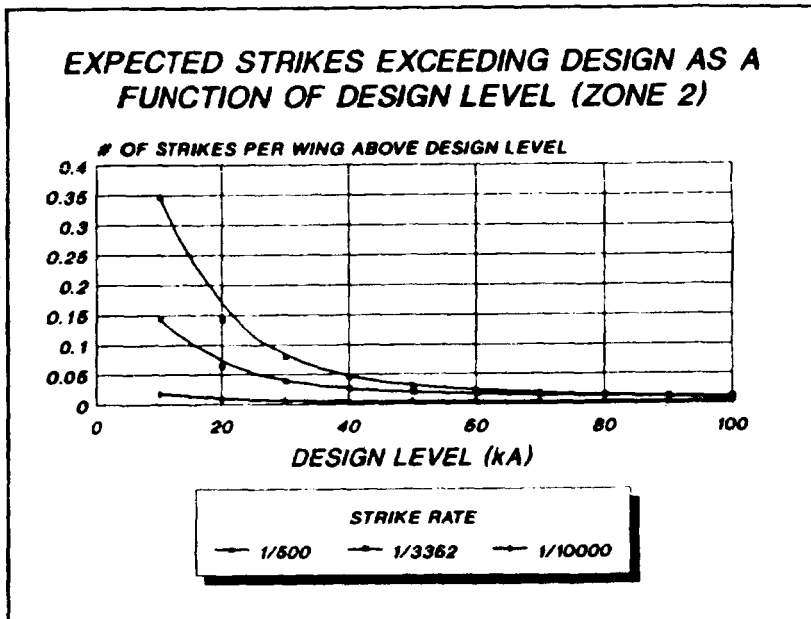


Figure 5. Impact of Changing Lightning Strike Rate.

CONCLUSIONS

The direct effects lightning test levels of MIL-STD-1757A appear to be highly conservative for lightning design guidance if areas on the aircraft structure exhibit a low probability of direct attachment. The tailoring of lightning design levels can be accomplished

Table III. Migration of Zone 1 Areas.

SPEED (KTS)	ALTITUDE (METERS)							
	500	1000	1500	2000	2500	3000	3500	4000
150	0.26	0.51	0.77	1.00	1.30	1.50	1.80	2.10
200	0.34	0.68	1.00	1.30	1.70	2.10	2.40	2.70
250	0.43	0.86	1.30	1.70	2.10	2.60	3.00	3.40
300	0.51	1.00	1.50	2.10	2.60	3.10	3.60	4.10
350	0.60	1.20	1.80	2.40	3.00	3.60	4.20	4.80
400	0.68	1.40	2.10	2.70	3.40	4.10	4.80	5.50
450	0.77	1.50	2.30	3.10	3.90	4.60	5.40	6.20
500	0.86	1.80	2.60	3.40	4.30	5.10	6.00	6.80

on a given platform if the dynamics of flight regime and threat remain relatively constant, however, this case history indicates that a relaxation of design levels below 60 kA for swept stroke regions can be hazardous. The manufacturer of the A-6 composite wing, using generally acceptable procedures outlined in MIL-STD-1795A, was able to justify a relaxation of MIL-STD-1757A swept stroke design levels from 100 kA to 40 kA for a portion of the wing surface. The disturbing finding of this study was that of the migration of the Zone 1 regions into the area of composite material which has shown inability to conduct these high currents without damage. Additionally, given the worst case scenarios by which all variables could be adversely affected simultaneously the mitigation factors become subordinate to the lightning protection deficiencies.

The A-6E composite wing lightning protection design appears sufficient for adequate protection to a reasonable lightning threat. The requirement for design levels for wing area 3, Zone 2 to be above 40 kA has been analyzed and found to be desirable but not absolutely necessary due to low probabilities of direct lightning interaction in these regions. The A-6 composite wing design features diminish, but do not eliminate the risk of catastrophic damage due to direct attachment of lightning to the composite structure.

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